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Pilot Study of a Novel Assistive Device to Improve the Biomechanics of Walking Gait in Populations with Foot Drop

A Thesis submitted in partial satisfaction of the
requirements for the degree Master of Science in Mechanical Engineering

by

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ABSTRACT

Pilot Study of a Novel Assistive Device to Improve the Biomechanics of Walking Gait in Populations with Foot Drop

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Erinn Kelly Sloan

Foot drop is a gait disorder characterized by weakness in the muscles that lift the foot. As a result, the foot tends to scuff the ground during the swing phase of gait. Previous work has demonstrated a treadmill that lowers one side of the tread while the affected foot is swinging forward will prevent scuffing. Preliminary results suggest that preventing scuff during swing can improve the biomechanics and rhythmicity of gait in populations with foot drop. However, the device is expensive and can only be used in the lab. Here we present a wearable passive assistive device in the form of a shoe that mimics the effects of the treadmill. Instead of eliminating contact with the ground, like the treadmill does, the shoe instead substantially reduces the scuffing forces through the use of low friction material on the sole. Critically, for traction during the stance phase of gait, the low friction material can retract into the shoe when the weight of the user is on the shoe. Compared to the treadmill, the shoe can be made for a fraction of the price, is more accessible for personal use, and can improve the daily lives of those with abnormal and impaired gait patterns. This paper presents the iterative design process of Cadence, as well as a feasibility study done with four adults with foot drop due to various neurological injuries. Results of the study show that the shoe immediately improves gait mechanics, speed over ground, and efforts of walking. All of the participants preferred walking in Cadence compared to walking in their normal shoes and other assistive devices. This initial study opens the door to future study for direct assistance and rehabilitative effects.

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1 Introduction

Hundreds of thousands of Americans have a stroke each year. Thousands of infants are born with cerebral palsy in the US each year [1]. Thousands more Americans have neurological disorders such as multiple sclerosis and ALS. A subset of all these people have a mobility disorder in common known as foot drop. Foot drop makes is difficult for the person to walk, as they cannot lift their toes and often scuff or trip on the ground. These populations have difficulties walking, balancing, and going about their daily lives with an impairment to their gait. The assistive devices and orthotics used to aid mobility are often uncomfortable or do not effectively prevent scuffing which would allow the user to walk with a healthy gait. Robotic rehabilitation devices are beginning to target these populations but a good solution that is cost effective and practical is not yet on the market.

This paper presents *Cadence*, an assistive shoe that aims to solve the problems with current assistive devices or rehabilitation techniques. The shoe is a passive device with retractable low friction regions on the bottom that reduce the forces of a scuff during the swing phase of gait, but still allow the user to take normal steps throughout the rest of the gait cycle. This paper also discusses a feasibility study conducted with four impaired individuals who all have varying severity of foot drop. Preliminary results showed that the two versions of *Cadence* tested improved the user's speed, improved gait mechanics to be closer to a healthy individual, and promoted a more rhythmic gait pattern. These results show *Cadence* has the potential to really change the lives of people with foot drop and is worthy of future studies and efforts to improve designs.

2 Background

Static brain injuries such as stroke and cerebral palsy are a leading cause of disability. In 1997, it was estimated that each year 795,000 Americans will have a stroke. This number is expected to steadily increase with the increasing age of our population [1]. Roughly three quarters of this population will be left with some form of motor impairment [2], [3].

Cerebral Palsy is a catch-all term used for static brain irregularities or injuries that take place before the age of two. Roughly 0.2-0.3% of children are born with cerebral palsy, or 8,000 per year in the United States [4]. This seems like a small number compared to people who suffer from a stroke; however the life expectancy of people with Cerebral Palsy is much longer than those post stroke. The prevalence of Cerebral Palsy is also postulated to rise as medicine saves more very-low-birth-weight infants [5]. By definition, 100% of people with cerebral palsy have motor impairment. These two categories, stroke and Cerebral Palsy, are lumped together in this paper because symptoms of the impairments are similar.

While symptoms of stroke and cerebral palsy vary from patient to patient, a subset of patients in each group will experience the inability to lift the foot up during the swing phase of gait. Failure to clear the floor and dragging the foot results from the condition of foot drop, but may also be caused by tight or spastic muscles of the hip or leg. Foot drop is characterized by the inability to dorsiflex, or lift the toes toward the shin, due to impaired control of the tibialis anterior and/or the triceps surae of the calf. It inhibits the rhythmic swing phase of gait, increases the probability of foot scuff and falls, and forces conscious monitoring of one's gait, typically manifesting into abnormal gait patterns.

Foot drop primarily affects the swing phase of the gait cycle, shown in figure 1. In order to clear the foot during this phase, impaired populations often develop atypical methods of walking to compensate for not being able to dorsiflex. Steppage gait looks much like marching or climbing stairs with excessive flexion in the hips and knee during the swing phase to lift the foot higher than normal to clear the floor. Crouch gait also involves excessive flexion of the hips and knees but this occurs through the entire gait cycle on both legs, looking much like a shuffle. A tip toe gait is when the person does not heel strike and instead keeps their weight on their toes throughout the gait cycle. Vaulting is common in groups with paralysis and is when a person does not flex their knee or hip, instead flexing the ankle of the planted foot midswing to lift their opposite leg higher. The final common compensation method is circumduction of the hip, where the leg swings out to the side during the swing phase. Each person with foot drop will develop their own unique gait that may be some combination of any of these compensation methods. However, most of these abnormal gait patterns are inefficient and can cause pain and discomfort since the joints and muscles are not being used the way they were meant to. Beyond the physical effects, walking with abnormal gait is distinct and may draw unwanted attention.

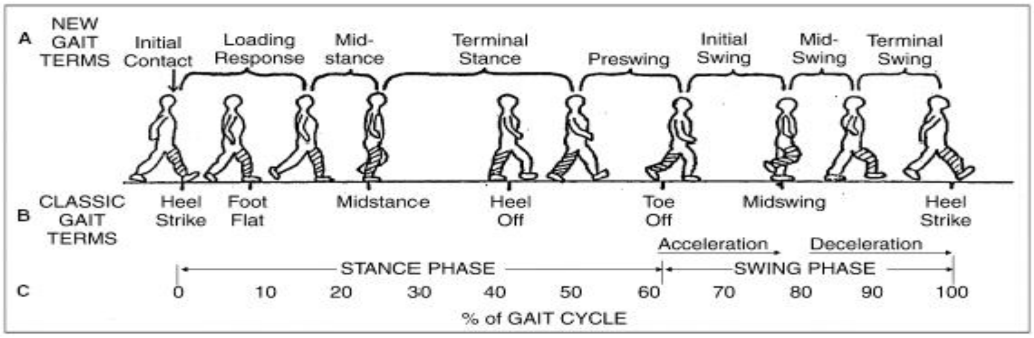

Figure 1. Phases of the walking gait with specific events detailed throughout the cycle. This paper uses the classic gait terms listed in row B [6].

Other conditions affecting the brain and spinal cord can also result in foot drop, such as brain tumors, nerve injuries, and other muscular or brain disorders like multiple sclerosis, ALS, and muscular dystrophy [7].

The cost to treat an ischemic stroke, caused by clots, under standard care is quite expensive at $140,000 lifetime cost per individual or $73.7 billion cost total in the United States [1]. Treatment for adults with Cerebral Palsy is not well studied in research, as efforts for treatment are done prior to the age of 18. However, initial studies suggest that adults with Cerebral Palsy can benefit from some of the same rehabilitative training as stroke patients[1], [9]. One week after the initial injury, movement disorders associated with static brain injury can be treated in one of two ways: assistive technology or rehabilitation.

Assistive technology refers to devices meant to aid a person in desirable tasks. Specifically for this research, the assistive technology will aid a patient in walking during their everyday life. This could include devices such as functional electrical stimulation (FES) applied to the tibialis anterior muscle or a static ankle foot orthosis (AFO). The FES device acts to supersede the centrally generated motor commands to apply activating potential to the tibialis anterior which acts to raise the toe during swing phase, compensating for a weak tibialis anterior muscle [10]. This common device enables more care-free walking for people with drop-foot, but it is cumbersome and somewhat painful over time. AFOs work to statically set the ankle angle of the paretic ankle such that it does not droop during swing phase, but it does not mimic healthy function of gait. Both of these technologies have been studied either by themselves or in conjunction with other protocol for rehabilitation but there is not enough evidence to conclude efficacy of long lasting neurological effects from either technology [11] mainly because the forces modifying the gait do not come from signals created by the injured brain. FES uses locally created electrical signals and AFOs use static external forces.

Aside from acute care directly following injury, also sometimes augmented by pharmaceuticals, rehabilitation is the only known treatment for neurological recovery. It works by forcing the origin of movement to come from the injured brain. In doing so, the brain reroutes internal connections to shift control of movement to non-injured regions [12], [13]. Of course, rehabilitation is expensive because the most prevalent form of movement rehabilitation comes from one-on-one training with a therapist. While the role of the therapist can never be replaced, it can be augmented by appropriate technology. The advancement of robotics has led to intriguing new ways to treat and study patient outcomes as robots can be precise movers and also precise recorders. In fact, as of 2010, the American Heart Association listed rehabilitation robots as a preferred method of treatment for upper extremity impairments [11]. The benefit from robotics comes from the volume of training that a robot can do in a short period of time. One study observed robotic training to consist of 1024 movements as compared to 45 movements done by a therapist in the same amount of time [14], [15]. If robots are responsible for the heavy lifting, a single therapist can be used with more than one patient at a time. Further, this paradigm can lessen the therapist's risk of occupational injury. This could lead to higher volumes of training for patients and lower associated cost per session.

For lower extremity impairments, and specifically walking, the effects of robots are a bit more clouded. In the same paper that recommends the upper extremity robots, lower extremity robots are said to be still in the infant stages [11]. This is in part because walking is a rhythmic activity. Upper extremity training can be done without the need for patient-driven rhythmicity, whereas walking is inherently rhythmic. Studies have shown that the brain encodes rhythmic motions much differently than it does discrete movements [16]. Getting a robot to predict the rhythmicity of the movement without interfering with patient initiated movements has proven somewhat elusive, even though admittance control is being attempted on the most significant robots [17]. In order to solve the contact problem of the foot dragging on the floor, researchers at Massachusetts Institute of Technology (MIT) developed the MIT-Skywalker [18], [19]. The system (shown in Figure 2) does not contact the leg but promotes healthy gait by removing the floor constraint during swing phase. During a month long study with three impaired subjects, the rhythmicity of gait significantly improved for two of three subjects, leading us to hypothesize the effect coming from the Skywalker's ability to remove the floor constraint [20]. The Skywalker, while promising, has two areas for improvement: cost and portability. If this device was to be sold in its current configuration, the cost for hardware alone would be approximately $1 million. The design is meant to be fixed and thus a patient could not bring it outside of the clinic. Rehabilitation is most effective with repetition so logic follows that a most useful device would be one that a patient could own or at least use regularly outside of clinical visits.

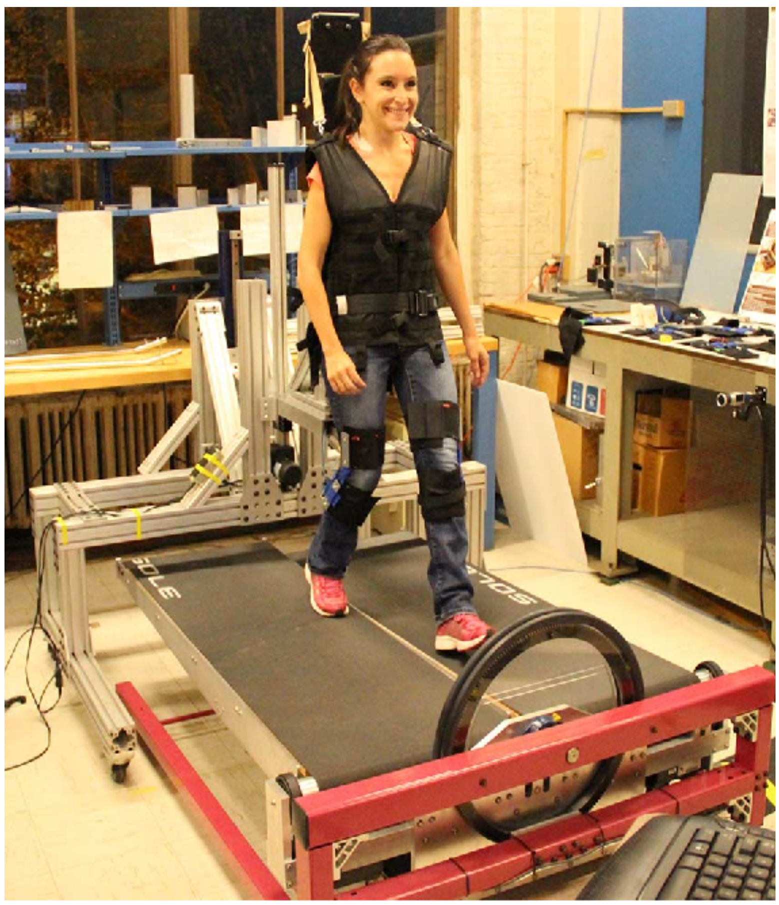

Figure 2. The MIT Skywalker robotic rehabilitation system

3 Designing Cadence

The prior studies by Principal Investigator, Dr. Susko, have shown that removing the floor during the swing phase via a robotic rehabilitation system (MIT Skywalker, seen in Figure 2) restores gait rhythmicity and promotes a faster walking speed [20], [21]. While the Skywalker made walking more comfortable during use and had lasting effects after training sessions, the two major drawbacks- cost and portability- left room to inspire the creation of *Cadence*. *Cadence* is a passive (no motors, batteries or electronics) shoe to replicate the rhythmic walking experience of the Skywalker. The development of this shoe began three years ago as a senior Capstone project for two separate teams. Initial estimates show costs can be cut by more than three orders of magnitude (1,000x) compared to the Skywalker system, and thus this could be a device that the patient owns to increase improvements in daily living.

The first prototype, in figure 3, was robotic in nature and intended to lift a platform like a garage door whenever a pressure sensor detected the opposite foot was planted. Weight and response times of the platform were the main two concerns for this version, preventing it from being tested with patients.

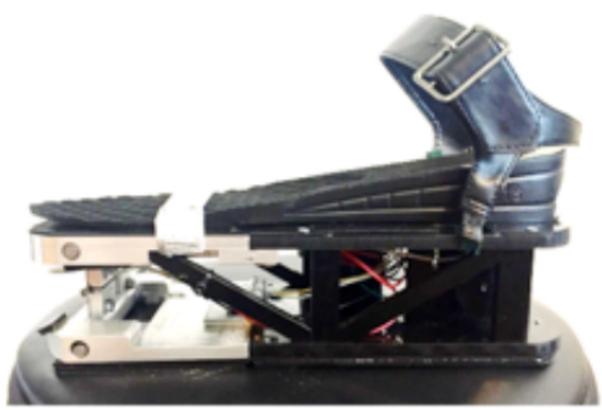

Figure 3. First iteration of the assistive shoe created as an engineering capstone project in 2016.

The next version in figure 4 was created by the second Capstone team. It has a retractable front platform that exhibits anterior-posterior translation if a foot scuff occurs; such movement of the shoe showed promise to recreate the effects of the Skywalker floor drops, while decreasing the horizontal force of a foot scuff in initial trials. Patients with foot drop exhibit less rhythmic gait than their neurologically normal counterparts, specifically because movement is more labored during the swing phase and thus less consistent. If the patient fails to clear the ground, a foot scuff will occur, which could induce a fall and will slow them down. During a scuff, the ground imparts a force on the swinging foot in the horizontal posterior direction, which causes an instantaneous deceleration, and a torque that acts to rotate the body forward. This increases the likelihood of tripping or falling. As scuff forces approach zero, the effective deceleration and body torque also approach zero and thus the effect of a foot scuff on the rhythmicity of gait will decrease.

Figure 4. The first prototype of *Cadence* created by an engineering capstone team in 2017 with a retractable front platform.

The shoe design has two features to minimize the scuff force:

1. For scuffs occurring with an angle between shoe and floor of greater than 15 degrees and for smooth walking surfaces such as hard flooring, the front edge of the shoe is constructed with a low coefficient of friction.
2. For low angles of scuff and for rough walking surfaces such as pavement, the shoe employs a retractable front platform which allows the scuff to send the front of the platform backward to limit interaction forces with the ground.

Initial performance testing of *Cadence* was done at the Heeluxe Laboratory (Goleta, CA) using a force plate and video-based motion capture. In comparison to a normal running shoe, *Cadence* showed a decrease in the horizontal scuffing forces by an average of 85% (7.4 pounds to 1.1 pounds). Plots from the study are shown in Figure 5.

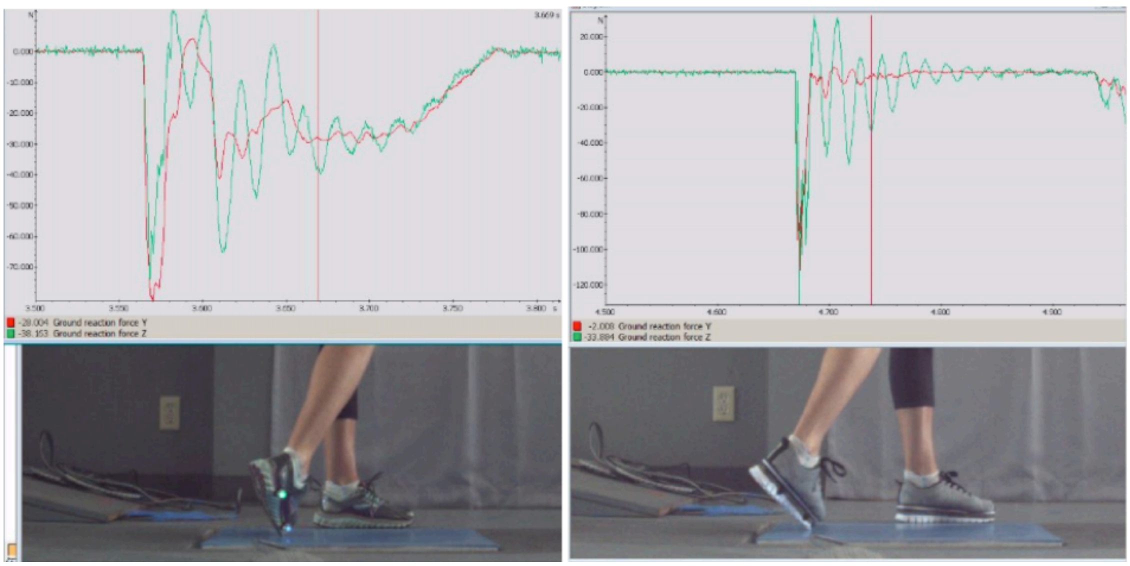

Figure 5. Force plate data with a normal running shoe (left) and Cadence (right) collected at Heeluxe Labs. Red plot shows the horizontal force of a scuff. The vertical red line indicates the mid-scuff position.

Before further development of the shoe, it was necessary to take a step back and redefine the constraints and needs of the device. An effective assistive shoe needs to perform like an ordinary shoe during the stance phase but reduce the "scuffing force" felt by the user during the swing phase. Any such mechanism must only actuate during the scuff. It cannot affect the user when they are accelerating/decelerating or on varying surfaces such as downhill gradients and stairs. As a means to better understand the needs of the shoe, the critical stages of the gait were examined. Three main events in the gait cycle where the foot changes contact with the ground are important to consider - toe off, the scuff mid swing, and the heel strike.

Toe off occurs when the leg entering swing phase is pushing off the ground to generate the forward motion. It is a relatively slow motion with high forces compared to a scuff. The forces are directed backwards and down onto the ground. The scuff will not have as much force behind it but it will occur much quicker than toe off or heel strike. The forces are directed generally forward into the ground, but at a much shallower angle compared to toe and heel strike. The heel strike (initial ground contact may actually occur at the midfoot or toes for those with foot drop) is less abrupt than the scuff and is more gradual like the toe off. The forces will be directed in the same direction forward and into the ground like the scuff. The magnitudes and directions of these different instances of ground contact are approximated in figure 6.

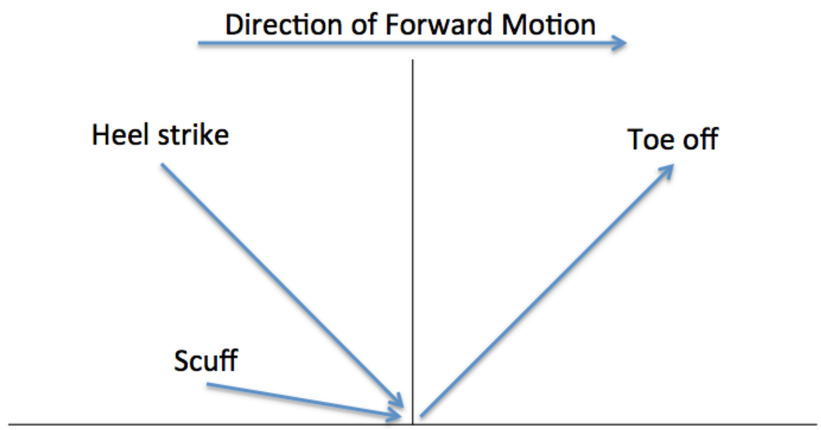

Figure 6. Diagram comparing the relative direction and magnitudes of the forces involved for a scuff (left), heel strike (middle), and toe off (right). The heel strike and toe off are high magnitudes relative to the scuff. However, the scuff event is at a much higher velocity relative to the heel strike and toe off, and therefore will have a shorter associated timescale.

The magnitude, direction, and speed of each of these events are significant design considerations to ensure the safety and effectiveness of the device. A mechanism that reduces forces for a scuff must not subsequently cause slipping to occur when the foot is being planted since the applied forces are in the same direction. The same idea would also apply to a downhill slope where forces are again in the forward direction. The second version of the *Cadence in figure 6*, for example, might prematurely retract on a downhill slope and no longer have a support under the toes when transitioning to toe off. In addition, the device must be directional such that a scuff could actuate a mechanism to reduce the force, but the toe off would not produce any actuation. The speed of these events is also significant because the scuff occurs significantly faster than either the toe off or heel strike. A mechanism that can distinguish the speed of the contact with the ground and only reduce forces during higher speed interactions would be ideal. With these considerations in mind, a number of new prototypes were developed in parallel throughout the year that fell into three main categories.

The first set of prototypes had wheels/rollers beneath the toes and ball of the foot, similar to the kids Heelys shoes of the early 2000s. Early versions of the wheeled shoes were simple to demonstrate the reduced scuffing force but did not account for the toe off constraint. To prevent slipping when pushing off the ground the wheels were constructed with one way bearings that only allowed rolling when sliding the foot forward. Any backwards motion would not spin the rollers, but would translate the force into the ground. Another attempt to create directional rollers used foam bumpers behind hinged rollers. The rollers would be fixed in place and allowed to spin when dragged forward on the ground, but any backward motion would rock the roller backward into contact with the bumpers to use friction to prevent spinning. Both of these prototypes worked well enough initially, but were complicated to manufacture, bulky, and unreliable. Another issue with this idea is that the rollers must be fixed in a certain orientation perpendicular to the swing direction. With such variability in gait from person to person, the shoe would have to be customized for each individual which is costly and impractical.

The next set of prototypes uses alternating types of stiff and viscoelastic foam to take advantage of the difference in speed of the events of the gait cycle. In each version of this shoe a low friction material was adhered to a viscoelastic foam replacing sections of the bottoms of shoes. Because of the viscoelastic properties of the foam and the lower forces during a scuff, the foam will remain stiff during the quick scuff and the low friction material will contact the ground. However, the toe off and the heel strike are slower and higher force so the foam will compress into the shoe, hiding the low friction material and allowing the rubber grip of the bottom of the shoe to dominate and prevent slipping. Figure 7 shows a cartoon of how the alternating types of foam would work. Early prototypes of this shoe worked well so development was focused on material choice, size and placement of low friction areas, and robust manufacturing techniques. The final iteration of this shoe, in figure 8, was made of a viscoelastic shoe foam used in the shoe industry and adhesive backed teflon sheets. The shape and placement of each low friction piece was approximated from the worn spots on the shoe of someone with cerebral palsy but would benefit from further refinement. This shoe was one of two shoes tested in the feasibility study that will be discussed later and will be known as the "foam" version of *Cadence*.

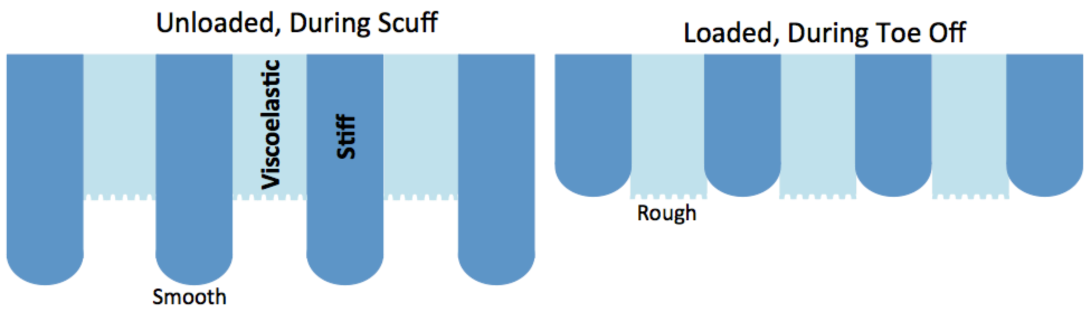

Figure 7. The alternating viscoelastic and stiff foams allow the low friction material to compress into the shoe when the foot is planted but will be exposed during a scuff.

Figure 8. Final iteration of the "foam" prototype that is tested in the feasibility study.

The final design, and the most promising of the three after the feasibility study, uses the same idea as the alternating foam but was inspired by the desire for omnidirectional wheels along the front of a shoe. Instead of patches of foam with a thin layer of low friction material, this shoe uses pegs of low friction delrin that sit inside low friction sleeves (figure 9). The pegs are attached to a similar viscoelastic foam inside the shoe. The pegs are cylindrical with rounded edges on the outside to allow a force from any direction to push it up into the shoe. The viscoelastic foam has the same function as the previous design, so that the low friction pegs are exposed to the ground during a scuff but retract into the shoe under higher loads during toe off and when the foot is planted. This shoe went through many iterations to find the right number, shape, size, and location of the pegs and a robust manufacturing process. The final version of this shoe worked best with low friction as close to the edges as possible to reduce friction as soon as any part of the shoe contacts the ground. This final version, known as the "button" shoe was the second modified version of *Cadence* used in the study.

Figure 9. Final iteration of the "button" prototype that is tested in the feasibility study.

4 Feasibility Study

4.1 Structure of the Study

To test the feasibility of the latest versions of *Cadence*, a study was developed to assess the changes in the mechanics of gait for people with foot drop and in healthy, unimpaired individuals. The study was approved by the Cottage Health Institutional Review Board and conducted in a gait lab on the UC Santa Barbara campus. The long term goal is to test this design for rehabilitation, as it follows the function of the MIT-Skywalker rehabilitation robot, but the first step in doing so was to prove that it can be a useful tool to improve gait mechanics and decrease the chances of falls during normal walking. If it can accomplish these goals, the shoe design has the potential to improve lives as an assistive device and will warrant a larger rehabilitation study.

The primary objective of this study is to compare the biomechanics and underlying muscle activation patterns of populations with drop-foot between normal running shoes and *Cadence*. The hypotheses are that while walking with the *Cadence* Shoe, as compared with an unmodified shoe, study participants will experience:

1. A lower variation of gait (better rhythmicity);

2. Hip, Knee and ankle angles during treadmill walking that more closely match healthy subject data;
3. Electromyography (EMG) muscle patterns that more closely match healthy subject data; and
4. Participant's experience through a survey indicating a more comfortable gait with *Cadence*.

Four people with varying degrees of impairment and foot drop participated in the first round of the study. They were first evaluated by a physical therapist according to the following inclusion criteria:

- Presence of drop-foot, defined as an observed inability to maintain functional dorsiflexion during the swing phase of gait
- Score of 0 or 1 on the Fugl-Meyer Assessment, Lower Extremity Assessment of Sensorimotor Function, Stage IV, Ankle dorsiflexion subsection
- Score of 3 or below on the Modified Ashworth Scale, measuring resistance during passive soft-tissue stretching and is used as a simple measure of spasticity
- The ability to ambulate independently for 6 minutes with or without the use of an assistive device
- Walk comfortably at a walking speed measured at or above 0.4mph for 10 meters

After being approved to participate by the physical therapist, the participant tried on an unmodified version of the shoe for fit. Each time they tried on a new shoe, and whenever using the treadmill, the participant was attached to a fall prevention harness for safety. This system consists of straps beneath the arms and around the chest that can be adjusted to the height of each user, all attached to an overhead track to allow the user to walk back and forth across the room without restraint. After adjusting to the new shoe, the participant performed speed assessments, followed by one minute of walking on a treadmill to record their motion. These two sets of tests were repeated for each shoe, starting with the unmodified shoe to first establish a baseline followed by the two versions of *Cadence*.

The speed test is a standardized test measuring the time it takes a person to walk 10 meters. There is a 2 meter acceleration and deceleration zone on either side of the 10 meter block to ensure the person is at full speed for the entire timed portion. The 10 meter walk test was conducted three times each and averaged for the participant's normal, comfortable walking speed and their maximum over ground speed while still maintaining safe control. A gait belt was used during these tests so that a physical therapist could intervene and support the participant's weight if they should stumble or fall.

The next test recorded the motion of the legs using two different types of sensors while the participant walked on a treadmill. Infrared sensors at discrete points on the legs and feet tracked the exact location of the body in a 3D space throughout time. Between 8 and 32 motion sensors were placed in specific points on the foot, lower leg, and upper leg, shown in figure 10. These sensors are individual LED trackers that each output a unique infrared signal so that they can be distinguished from one another. Six cameras positioned around the lab captured and recorded the infrared signals, producing a three dimensional view of the x,y, and z location of each tracker at any moment. Simultaneously, the muscle contractions in the lower legs were recorded using Trigno Flex EMG sensors placed on the soleus and the tibialis anterior on each leg, the muscles that control dorsiflexion of the foot.

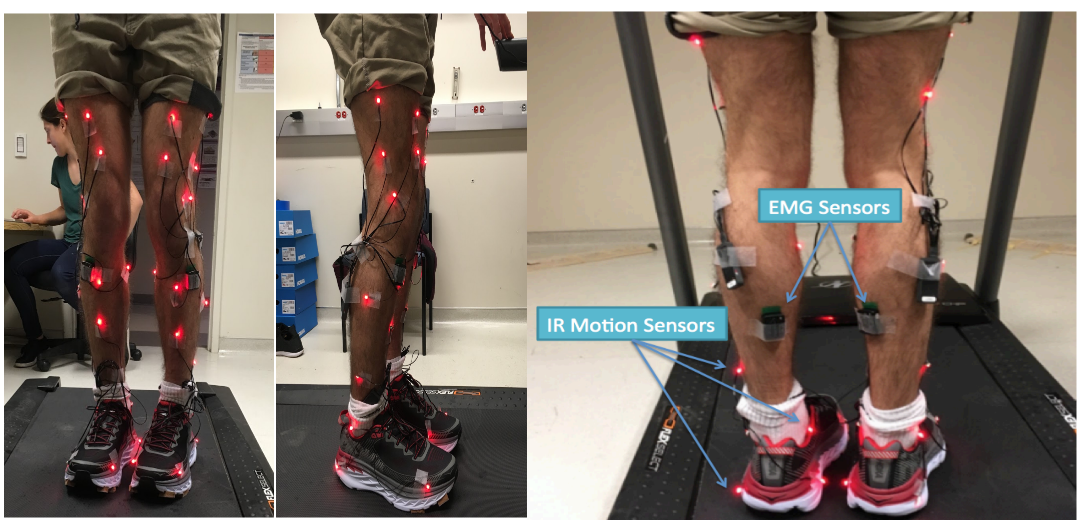

Figure 10. Placement of the EMG and motion capture sensors on a participant.

4.2 Healthy Subjects

In addition to testing the feasibility of the shoes on impaired individuals, it was important to demonstrate the shoes do not impact healthy walking gaits. Three healthy subjects went through the the speed trials as a control group given the same set of instructions as the impaired group. None of them have history of any gait or mobility issues, and represent what a healthy person's gait should look like. No significant changes were found in the physical qualities of their gait or walking form before and after wearing either version of *Cadence*. The difference in speed of the healthy subjects, as measured during the 10 meter test, was between 0% and 5% which is insignificant compared to the changes that will be discussed later with the impaired populations. This is summarized in figure 11. There was very little variance between each speed test and the mechanics of each step demonstrate the rhythmic gait of a healthy individual, regardless of which shoe was worn. Since each of their gaits looked relatively identical between the three shoes, it can be concluded that the shoe does not affect the healthy gait. It also shows that the changes seen in the other participants are a combined result of the shoe and how it affects incorrect gaits. Should a user's gait improve enough to be considered healthy, the shoe should not hinder them or negatively affect their gait. Any improvement can also be attributed to the shoes themselves.

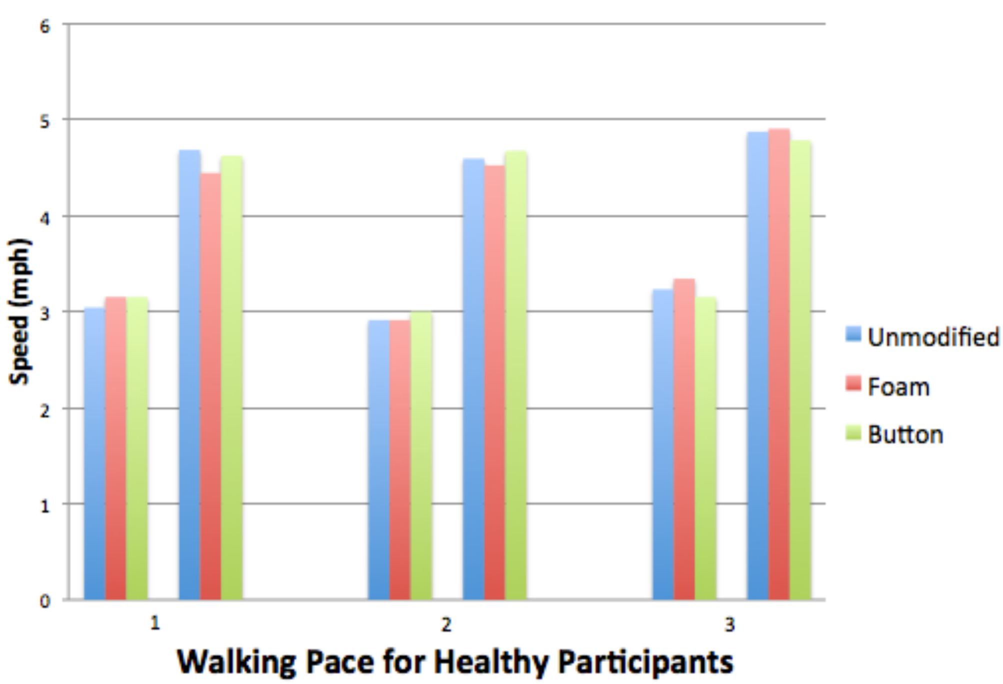

Figure 11. Healthy subject speed trials showing little to no difference in pace between unmodified and modified shoes.

4.3 Collecting Data with Impaired Subjects

Three of the four impaired individuals participating in the study have very similar gait mechanics, all using circumduction of the hip to clear the floor with their foot. Therefore, they are later grouped together and compared to one another based on the similarities in their natural gait. Three data sets were obtained and compared to determine how each shoe changed the gait of the participants: the angle the leg swings out at, speed, and amount of time the foot drags and is in contact with the ground. Unfortunately, the EMG data collected for each of these participants is not useful because they all experienced partial paralysis in their lower extremities and could not contract the muscles being monitored. There was minimal to no muscle contraction detected, let alone a change between each of the shoes.

The angle of circumduction is used to show how far out the leg has to swing in order to provide clearance for the foot. Healthy gait would be nearly zero for the angle, when the leg passes under the centerline of the body. This angle was determined using the motion capture data of two sensors on the leg for each person. The first sensor was on the outside of the affected ankle for each participant. However, the second sensor chosen differed slightly between participants depending on the camera views of the sensors, but was located higher on the outside of the affected leg, in line with the first sensor. Sometimes sensors would be blocked from the view of all 6 cameras by clothing, other body parts, or the treadmill. Therefore, the most consistent of three sensors throughout all the trials was chosen for each person. To be consistent, the angle recorded was chosen each time the two sensors shared a y coordinate (y-axis is defined as the frontal plane) during the swing phase. Figure 12 depicts an example of two sensors being used to determine the angle of circumduction.

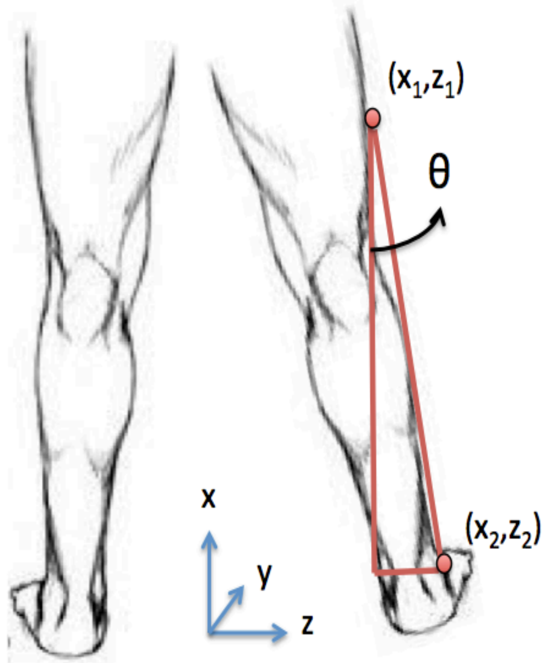

Figure 12. Using two motion capture sensors to determine the angle of circumduction. The red circles represent the sensors whose coordinates are known. The y coordinates of the sensors match when the moving leg crosses the frontal plane and also when the foot is farthest away from the centerline of the body. At this time the x and z coordinates are used with geometry to determine the angle of circumduction.

To maintain consistency, the angle was calculated from the coordinates of the sensors whenever the moving (affected) leg crossed the frontal plane and the foot is farthest from the centerline of the body. This is consequently when the y coordinates of the two sensors match during the forward swing. At this point in time, the x and z coordinates were used along with simple geometry to determine the leg angle pointed out in the figure. The angles calculated for each shoe were averaged over a least a dozen steps for each participant.

The speed tests outlined previously were averaged to determine whether or not the participant would walk more quickly in the different shoes tested. The same 10 meter speed trial was run three times each, at two different speeds, in each type of shoe. Gait will change slightly depending on the speed a person is walking, so the trials were run at both the participant's comfortable, natural pace and at the fastest pace they felt safe walking. This was meant to emphasize any slight changes that speed may affect in their gait to better understand how the shoe affected each person.

The amount of time the foot is in contact with the ground during a swing shows how long a scuff is and depends on the compensation method of each person. It was calculated as a percentage of the time that the affected foot is in contact with the ground between toe off and planting again, for one half of a full gait cycle (one step). The data presented later for this was averaged over at least a dozen steps for each participant in each shoe. Some participants did not scuff at all, while others never lifted their feet from the ground, so this was an insignificant data set for them. For the rest, however, it could indicate how reliant they are on the different types of shoes and quantify how their scuffing is affected. The compensation methods these impaired populations develop often prevent some scuffing, but do not always prevent all of the dragging characteristic of foot drop. For healthy gaits, the time the foot drags would be zero, but someone with foot drop will likely drag their feet throughout the swing phase if they were not using a compensatory strategy such as circumduction, hip vault or crouch gait.

4.3.1 Participant 1

Participant 1 has multiple sclerosis affecting the right side of her body with numbness and partial paralysis below the knee. She normally walks with an ankle-foot orthosis (AFO) to keep her ankle bent and allow her to swing her foot underneath her body. Without the AFO, she compensates with both vaulting and swing leg circumduction. She not only flexes the planted ankle and lifts her opposite hip up, but also swings the other leg out and around to complete a step. She wore the AFO during initial evaluations, but chose to remove it for the study. This unnatural gait is not only inefficient but also causes discomfort in joints and muscles that are not being used correctly.

In the foam version of Cadence, Participant 1 increased her comfortable walking speed and her maximum speed by 34.5% and 18.6% respectively compared to the control shoe, shown in figure 13. Portrayed in figure 14, the angle between her ankle, hip, and vertical decreased 25.2% (from 7.7 degrees to 5.7 degrees). The standard deviation of these measurements was similar for the normal shoe (1.3) and the foam version (1.65), which shows the steps were not necessarily more similar, or rhythmic in this case. This participant dragged her feet on the ground the entire time she walked so there was nothing to compare between the shoes for the metric of how long the scuff lasted per step.

In the button version of Cadence, tested second, participant 1 increased her comfortable walking speed and her maximum speed by 54.8% and 24.0% respectively compared to the control shoe. The hip angle was reduced by 52.7% (from 7.7 degrees to 3.6 degrees) and a standard deviation, 0.71, that was half that the other two shoes. The significantly smaller standard deviation implies less variance between each of the steps which is characteristic of a more healthy gait.

Overall, both shoes showed significant improvement in the speed and mechanics of this participant's gait. Being able to walk closer to a healthy gait, with less circumduction, is not only more healthy but a quicker and more efficient motion which helps explain the increase in speed.

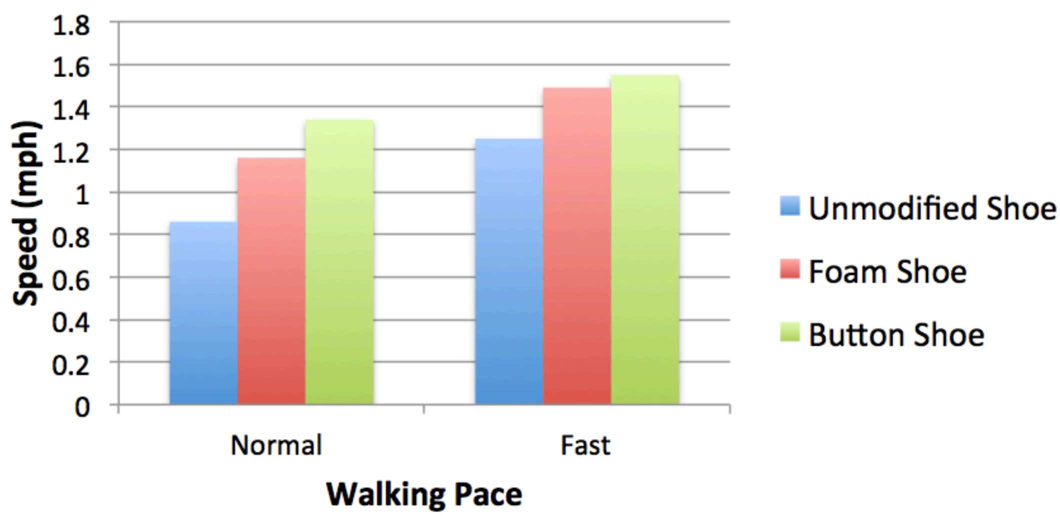

Figure 13. Summary of the speed test data for participant 1. She showed improvements for both walking speeds in both of the modified shoe, with the best improvements for the button shoe.

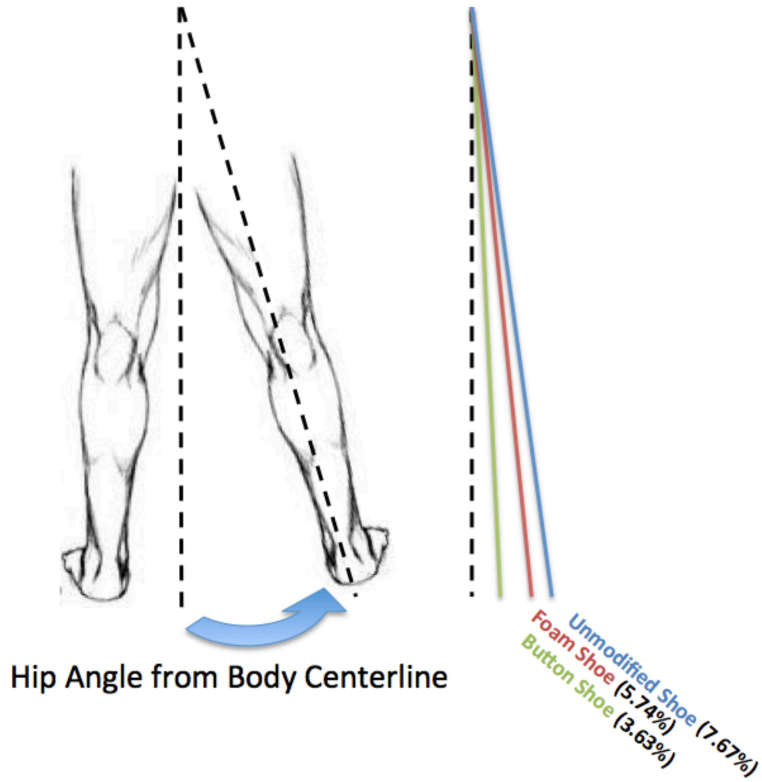

Figure 14. Summary of the motion capture data showing hip angles for participant 1. She showed improvements in both shoes with the button shoe being the most significant.

4.3.2 Participant 2

Participant 2 had a brain tumor removed that resulted in the complete paralysis of his right leg. He also wears an AFO and circumducts during the swing phase of his gait. He has balance issues and is very slow compared to all of the other participants. As a result, the speed tests were only conducted using the button shoe to save time during the study. The treadmill test was shorter, so motion capture data was able to be collected for all three shoes. The results are summarized in figures 15-17.

In the button version of Cadence, Participant 2 increased his comfortable walking speed and his maximum speed by 8.8% and 46.9% respectively compared to the control shoe. The angle between his ankle, hip, and vertical decreased 41.4% with a standard deviation of only 0.41

compared to 1.52 in the unmodified shoes. Similar to the previous participant, this shows the circumduction was significantly decreased and each step was more rhythmic in the button shoe. In the foam version of Cadence, participant 2 the hip angle was reduced by 56.8% and a a standard deviation of 0.63.

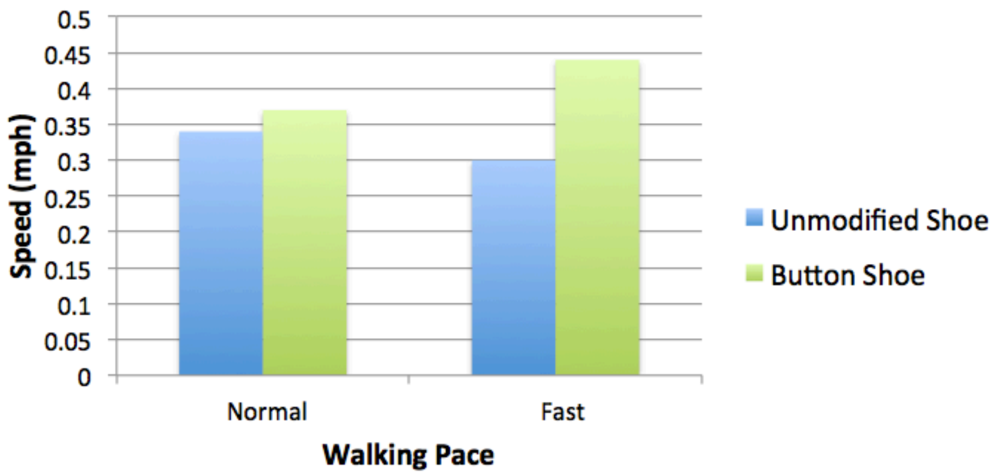

Figure 15. Summary of the speed test data for participant 2. Minimal improvements were seen for the comfortable walking pace, but the fast walking pace significantly increased in the button version of the shoe.

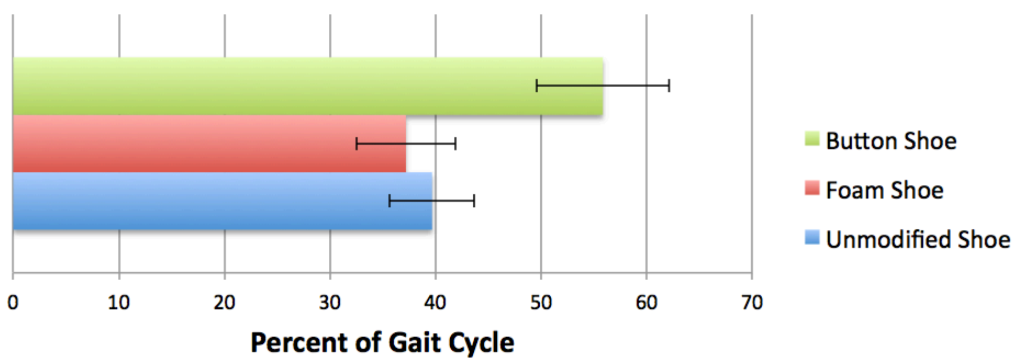

Figure 16. Data showing the amount of time the foot scuffed during the swing for participant 2. The percentages are only for a half step, rather than the full gait cycle since only one foot is impaired.

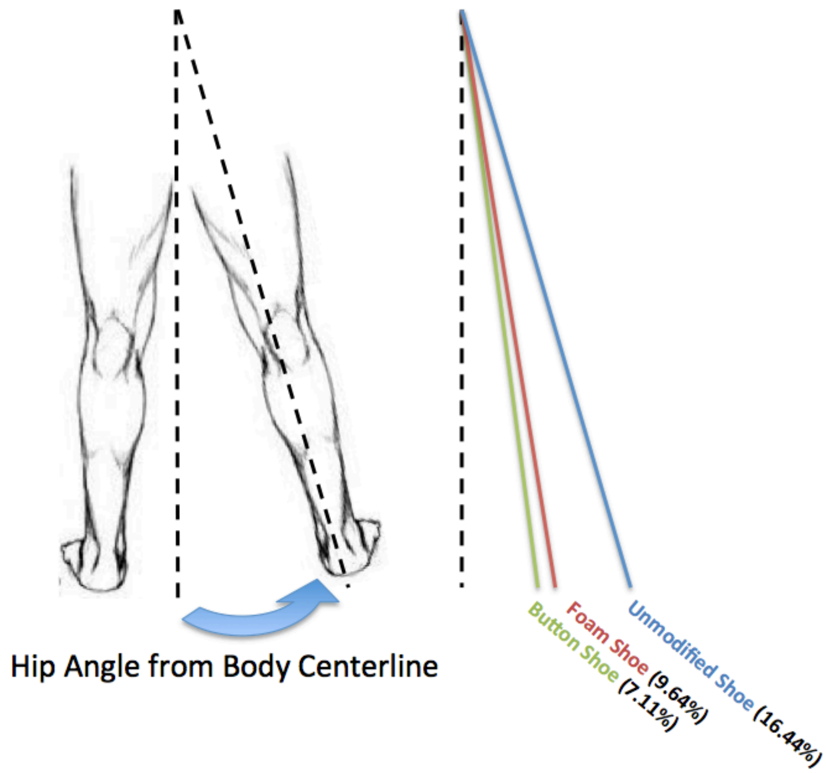

Figure 17. Summary of the motion capture data for participant 2 showing hip angles. Both the foam and the button versions of the shoe showed significant improvements in the hip angle compared to his normal gait.

The final metric measured for this participant was the percent of the swing phase that the shoe was contacting the ground. This participant normally drags his foot for 36% of the swing phase, but significantly increased the amount of time his foot was on the ground with the other two shoes. With the foam shoe his foot was on the ground for 55.4% of the swing phase and 60.5% in the button shoe. Combined with the reduced hip angle, this shows the participant is showing improvements in his gait mechanics and engaging the low friction parts of the Cadence shoes more often. Cadence is better able to help him as he reduces his reliance on the incorrect compensation methods he developed. Overall, both shoes showed improvement in the speed and mechanics of this participant's gait.

4.3.3 Participant 3

Participant 3 has cerebral palsy and relatively mild foot drop compared to the other participants. His gait is characterized by excessive flexion in the hip and ankles, but doesn't have a significant compensation method to prevent scuffing. His speed actually decreased with the two new shoes compared to unmodified ones. He was the fastest of the participants and walked at a "normal" speed that the healthy research assistants were also comfortable at.

In the foam shoe, he decreased his comfortable speed by 20.3% and and his maximum speed by 2.1%. Similarly, for the button shoe he decreased his comfortable speed by 10.6% and his maximum speed by 1.8% compared to unmodified shoes. Scuffing doesn't seem to be much of a problem for this participant in normal shoes. Based off the participant's feedback and seeing no significant change in gait by visual observation, it seems like the unfamiliar shoes made him hesitant and slow down as a precaution. The shoes did not appear to change the mechanics of his gait at all, so it was likely a subconscious decision to slow down in a new situation. This is consistent with the speed results if you compare the two new shoes to one another. The first new shoe he wore was a much larger decrease in his overall speed than the second shoe he tried on. So if the shoes aren't really affecting his gait, then there would not be a major difference between either of the versions, except the amount of time he spent in them. The second pair of shoes may have slowed him down less as he got more comfortable wearing the strange shoes in general. It wasn't necessarily the shoe itself that made the difference, but that he was not as hesitant in the second pair. Similarly, the fast walking pace may have given more similar results between the different shoes because the participant was more focused on going at a quick pace than being thrown off by new shoes. The participant seemed to agree with this based on a discussion after the trial was complete.

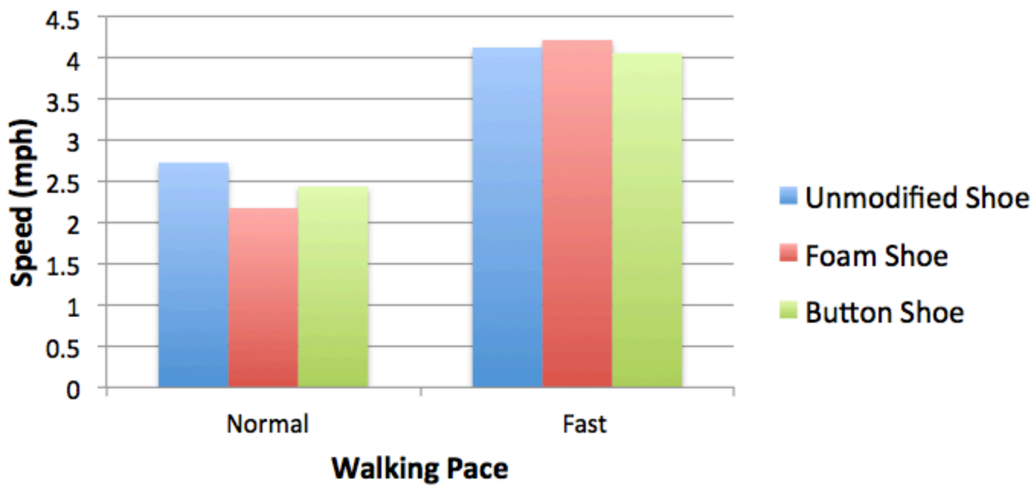

Figure 17. Summary of the speed test data for participant 3. He showed no change in his gait mechanics so only the speed data showing him slowing down is included here.

4.3.4 Participant 4

Participant 4 had a tumor removed in her brain that left the left side of her body partially paralyzed, affecting the lower leg the most. She normally walks with an AFO and a walker to assist her. Even with both assistive devices, she compensates with leg circumduction like the first two participants. The AFO was not used in any of the trials, but the walker was used during the speed tests to make the participant more comfortable. No assistive devices were used on the treadmill. The results are summarized in figures 19- 21.

In the foam shoe, participant 4 increased her comfortable walking speed by 16.0% and her maximum speed increased by 3.7%. Her hip angle for circumduction decreased 21% compared to her gait in unmodified shoes. The foot contacted the ground about the same amount of time during the swing phase between the foam and normal shoes, with only a 2% difference and a very similar standard deviation (indicator of rhythmicity).

More significant changes were seen with the button shoe for this participant. Her comfortable walking speed increased 19.7% and her maximum speed increased 22.8%. The hip angle decreased 65.7%, however the standard deviation was similar to the angle being measured in unmodified shoes. Even with the relatively high standard deviation, the maximum angle measured for the button shoe was still 20% less than the angles in the unmodified shoe. In addition, the participant was contacting the ground 30% longer in the button shoe than either of the other two shoes. Overall, there were significant improvements in the speed and mechanics of the gait for this participant as well.

Figure 19. Summary of the speed test data for participant 4. She showed improvements in all categories and had the best improvements in the button shoe. The button was the first trial conducted of the new shoes.

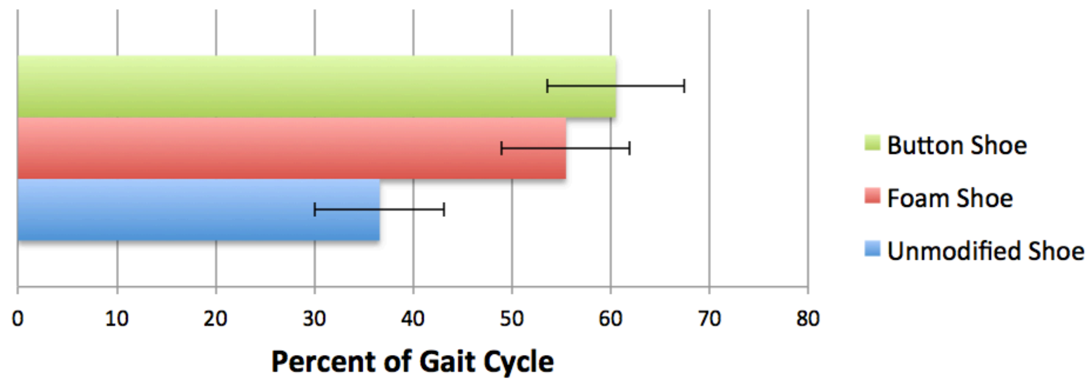

Figure 20. Summary of the amount of time a scuff occurred during the swing phase for participant 4. She showed improvements in all categories and had the best improvements in the button shoe.

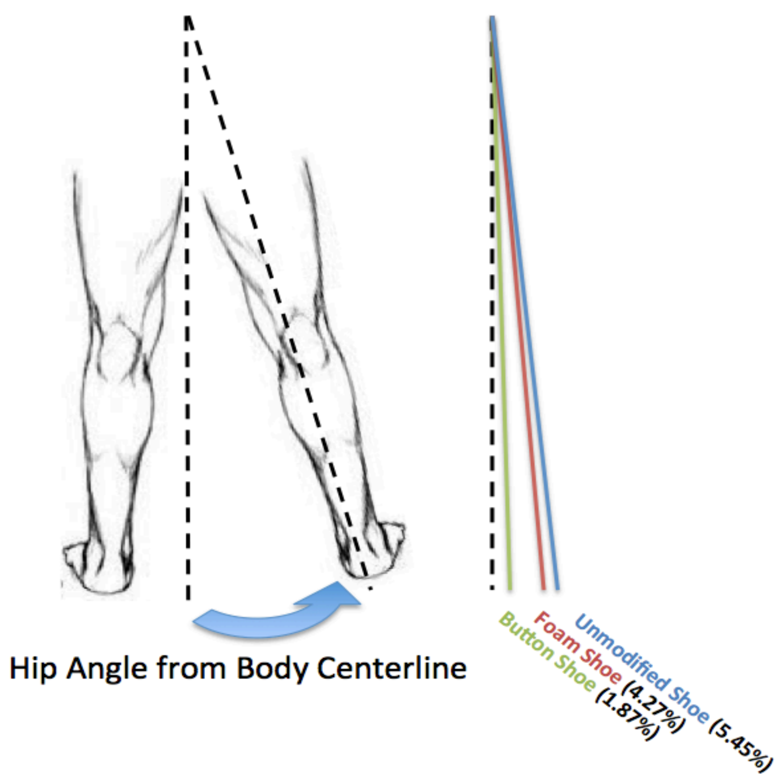

Figure 21. Summary of the motion capture data showing hip angles for participant 4. She showed improvements in all categories and had the most significant improvements wearing the button shoe.

5 Discussion

Comparing the participants that circumduct (1,2,4), there are some patterns that emerge amongst them. Table 1 shows a quick summary of the relative improvements of each shoe for each participant in the categories tested. Positive boxes mean the participant improved, and double positive was a large improvement. Similarly a negative box means the participant did worse in a category and double negatives are very poor. A box with "0" means there was an insignificant change. The greatest differences in results between the unmodified and modified shoes are both the speed increase and the angle decrease for each of them. All three of these participants significantly reduced their circumduction and sped up when wearing the two versions of *Cadence*. In addition, participants 2 and 4 showed increased contact between the shoe and the ground during the swing phase. For participants 1 and 4, the button shoe showed more improvement in gait mechanics and speed. Participant 2 could not be included in this comparison because he did not complete the study in the foam shoe due to time constraints.

Table 1. Summary of the relative improvements to the biomechanics of each participant.

	Speed		Angle		Time on ground	
	Button	Foam	Button	Foam	Button	Foam
P1	++	+	++	+	N/A	N/A
P2	++	+	+	+	++	++
P3	-	- -	- -	-	N/A	N/A
P4	++	N/A	+	++	++	0

Another thing to consider was the order that the two shoes were tested for each participant. If the button shoe gave better results, it needs to be because of the shoe and not the order in the testing protocol it was worn. Factors such as fatigue or getting used to the new shoes could have an impact on the outcome. Participants 1 and 4 tried the shoes in a different order, with the last participant starting with the button instead of the foam shoe. There were only two different orders to serve as an example but both participants had more significant improvements (and better feedback) for the button shoe, regardless of the order they tried them. Future studies should keep this as a consideration and randomize the order of testing to confirm it does not affect the outcomes of the results.

In the participants that circumduct (1,2,4), the comfortable speed tests showed much larger differences than the maximum speed tests. This makes sense because there is more room for change at the slower pace. At some point, the participants can only walk so fast, so the maximum speed tests are less likely to show the big shifts compared to the comfortable speeds. Based on feedback from the third participant, he wasn't used to the shoe and was more hesitant during the comfortable speed test. However, trying to go his maximum speed made him forget about the shoe and any cautious walking he was doing to allow it to drag and assist his walking more. This explains why he does not fit the trend like the others.

The amount of time the foot spends on the ground during the swing phase warrants more description. For the two participants this was relevant to, they each had their foot contacting the ground longer in the prototypes than in the unmodified shoe. At first this would seem like the scuffing is worse, however, it can also been seen as a positive. These two participants did scuff, but it was not so significant that they would trip or fall. Instead, their foot slid as they walked and the mechanics of their gait improved. The low friction and ability to slide the foot allowed the participants to walk with better form, more quickly, and more easily. They relied on the shoe to help them get their foot under their body rather than the improper compensation methods affecting their gait. While the increased contact with the ground and increased reliance on the shoe are not part of a perfect gait, the improvements in gait mechanics were significant and could lead to long term benefits.

A major factor in improving the gait of these impaired populations is returning the rhythmicity to their steps, where each step is similar to the one before it, and which comes from a different part of the brain than the discrete movements. The motion capture system with the LEDs was meant to provide data to measure the rhythmicity, much like what was done for the MIT Skywalker. While useful data was obtained with the motion capture, more work is needed to improve its application to this study. The placement of the cameras, LED markers, and treadmill all played a factor in the quality of data obtained. Many of the markers did not provide consistent enough data to track the motion of its designated part of the leg sufficiently. This would have allowed a better picture of where every part of the foot and leg were in relation to one another. Some markers for each participant were consistent enough to provide the data for the hip angle. In addition, the standard deviation of those hip angles could give some idea of the rhythmicity of gait in the different shoes. A small standard of deviation for that hip angle, as well as the time the foot contacted the ground, implies that each step was very similar during that trial. Results for each of the participants showed decreasing trend that could imply an improvement to rhythmicity. The first two participants showed lower standard deviations across all their data measurements, which would imply more regular steps and less variance between the steps. This implies increased rhythmicity in their gait for the two new shoes. The third participant did not show changes in his gait so it also makes sense that the standard deviation on his measurements was comparable before and after. His rhythmicity then was not affected by the shoes. The final participant was an exception, however, and seemed to increase the variability between her steps based on the standard deviation measurements, but it was not too significant. In addition, the laborious compensation methods these impaired populations develop adds to the lack of rhythmic gaits. If the shoes with low friction can make it easier to walk even as a discrete movement, then there is a better chance of rhythmicity returning in the future. Further study of the motion capture, looking at more participants, and giving the participants more time to get used to the shoes could confirm that the *Cadence* device may return the rhythmicity of gait to the user as hypothesized.

While there were many steps to average over and look at the standard deviation for each participant, this initial study does lack a strong statistical significance. There were only four participants, each with a unique gait. Some of the data collected could only be compared between two or three of the participants. While efforts were made to keep the study consistent, there are many variables between the participants that could not be avoided, such as the construction of the shoes of different sizes. Further studies with many more participants of various gait imperfections will be needed to really understand how these shoes affect those with mobility issues. However, despite the variables and few participants, *Cadence* received great feedback and immediately impacted its wearers.

All of the improvements observed in the participants occured within minutes of trying the new shoes. They were given identical instructions for each trial and were never instructed to walk different, so the changes observed were organic and not forced by suggestion. The circumduction gait that three of the participants have had for years was immediately reduced and became more normal/healthy with the new shoes. This shows promise for a shoe that can make it easier and more natural to walk.

Beyond the quantitative data collected, each participant was polled about the different shoes and gave personal feedback after walking in each of them. All of the participants agreed both the foam and button versions of *Cadence* were preferable to their normal daily shoes, including the participant that admitting hesitating in the new shoes at first. Furthermore, they all agreed that the button shoe felt like it was the easiest to walk in and felt it had the most effect on their gait. An important note most of them pointed out was that the button shoe sounded strange as it clicked on the ground which made them nervous until they had more time to get used to it. There was general consensus that the more time spent in both shoes, the better they felt and the more willing they were to put trust in the mechanism and the concept. The time to get used to the shoe was especially important in the button version since it was more unfamiliar. Despite being nervous at first, each participant agreed the button version was their favorite. Even the participant that did not improve thought that the shoes made it easier and more comfortable for him to walk even if no real quantitative changes were observed. They all had positive feedback with little negative to say except small details about the fit or look of the shoe. They said these shoes were comfortable and they could not feel the raised low friction parts beneath their foot, but one participant thought the shoe used was not supportive enough for his ankle weakness. A common request was also if these shoes could be made to look less like an athletic shoe and something that would be more appropriate for daily use. This feedback will all be taken into consideration for future prototypes to hopefully improve the design and make it accessible to a bigger population.

6 Conclusion

After dozens of prototypes and iterations, hours of trials with several impaired adults, and the feedback from people who actually felt immediate changes to their gait upon trying on *Cadence*, there is hope for an assistive device that is accessible for personal use and can improve daily life for people with foot drop. Revisiting the hypotheses presented earlier shows very positive initial results for *Cadence*:

- ✓ A lower variation of gait (better rhythmicity);

✓ Hip, Knee and ankle angles during treadmill walking that more closely match healthy subject data;

✗ Electromyography (EMG) muscle patterns that more closely match healthy subject data;

✓ Participant's experience through a survey indicating a more comfortable gait with *Cadence*.

Based on the results of the feasibility study, *Cadence* as an assistive shoe has a promising future. Three of the four participants improved many aspects of their gait including the mechanics and speed. The remaining participant did not improve but his gait mechanics were unchanged physically, so the shoe likely had no effect on him other than requiring caution due to unfamiliarity with the shoe. The participants that improved showed major changes in their gait that would benefit from further analysis. So far just a few aspects of gait mechanics were analyzed but many other factors such as stride length, part of the foot contacting the ground when planting, and the variance in location of certain parts of the leg throughout the gait cycle could be obtained with the data already collected. This would further support the potential for rhythmicity improvements with these shoes. Future studies could also benefit from adding a force plate to the study to characterize the forces that occur upon toe off, heel strike, and mid swing scuffs. This information and what is already collected from this study can be used to further develop and refine the *Cadence* prototypes.

Overall, the *Cadence* shoe had quite a positive impact. They were excited that a shoe was being designed for their specific needs and hopeful that walking actually felt more comfortable and proper than it had in years. With more development, this is an assistive device that not only can improve the gait of populations with drop foot, but can return a sense of normalcy to the daily lives of people with a variety of mobility disorders.

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8 Appendix

8.1 Institutional Review Board Approved Protocol

Informed Consent forms completed (10 minutes)
Baseline clinical testing in normal shoes (16 minutes)
Treadmill walking acclimation with fall prevention system - 2 minutes
Break (sensors applied) – 5 minutes
Sagittal plane motion capture on treadmill - knee angle, ankle angle, ankle position, EMG – 1 minute
Normal and maximum over-ground walking speed test done with stopwatch in the hallway outside of the D4H laboratory – 5 minutes
Break to change shoes, remove treadmill – 3 minutes
Testing with Cadence – Configuration 1 (16 minutes)
Acclimation of the shoe with fall prevention system – 3 minutes
Break – Replace Treadmill under fall prevention system – 2 minutes
Treadmill walking acclimation with fall prevention system - 2 minutes
Sagittal plane motion capture on treadmill - knee angle, ankle angle, ankle position, EMG – 1 minute
Normal and maximum over-ground walking speed test done with stopwatch in the hallway outside of the D4H laboratory – 5 minutes
Break to change shoes, remove treadmill – 3 minutes
Testing with Cadence – Configuration 2 (16 minutes)
Acclimation of the shoe with fall prevention system – 3 minutes
Break – Replace Treadmill under fall prevention system – 2 minutes
Treadmill walking acclimation with fall prevention system - 2 minutes
Sagittal plane motion capture on treadmill - knee angle, ankle angle, ankle position, EMG – 1 minute
Normal and maximum over-ground walking speed test done with stopwatch in the hallway outside of the D4H laboratory – 5 minutes
Break to change shoes, remove treadmill – 3 minutes
Conclude - remove all sensors (2 minutes)

8.2 Fugl Meyer Chart

The Fugl Meyer Chart, Subsection Lower Extremity Assessment of Sensorimotor Function, Stage IV, Ankle dorsiflexion subsection

3b. Ankle Dorsiflexion:
• Patient is sitting, feet on floor, with knees free of chair. Calf muscles should not be on stretch.
• Have patient perform movement with unaffected side first.
• On the affected side, check patient's available PROM at the ankle joint.
• Patient is instructed to "keeping your heel on the floor, lift your foot."
• Test 3x on the affected side and score best movement.
	• *Scoring* (Maximum possible score = 2):
	  • (0) – No active motion
	  • (1) – Incomplete active flexion (heel must remain on floor with medial and lateral borders of the forefoot clearing the floor during dorsiflexion)
	  • (2) – Normal dorsiflexion (full within available ROM, heel remains on the floor)

8.3 Modified Ashworth Scale

Modified Ashworth Scale Instructions

General Information (derived Bohannon and Smith, 1987):

- Place the patient in a supine position
- If testing a muscle that primarily flexes a joint, place the joint in a maximally flexed position and move to a position of maximal extension over one second (count "one thousand one")
- If testing a muscle that primarily extends a joint, place the joint in a maximally extended position and move to a position of maximal flexion over one second (count "one thousand one")
- Score based on the classification below

Scoring (taken from Bohannon and Smith, 1987):

0	No increase in muscle tone
1	Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion when the affected part(s) is moved in flexion or extension
1+	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM
2	More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved
3	Considerable increase in muscle tone, passive movement difficult
4	Affected part(s) rigid in flexion or extension

Patient Instructions:

The patient should be instructed to relax.

8.4 10 Meter Walking Test Instructions

Timed 10-Meter Walk Test

<u>General Information:</u>

- individual walks without assistance 10 meters (32.8 feet) and the time is measured for the intermediate 6 meters (19.7 feet) to allow for acceleration and deceleration
    - start timing when the toes of the leading foot crosses the 2-meter mark
    - stop timing when the toes of the leading foot crosses the 8-meter mark
    - assistive devices can be used but should be kept consistent and documented from test to test
    - if physical assistance is required to walk, this should not be performed
- can be performed at preferred walking speed or fastest speed possible
    - documentation should include the speed tested (preferred vs. fast)
- collect three trials and calculate the average of the three trials

<u>Set-up (derived from the reference articles):</u>

- measure and mark a 10-meter walkway
- add a mark at 2-meters
- add a mark at 8-meters

<u>Patient Instructions (derived from the reference articles):</u>

- Normal comfortable speed: *"I will say ready, set, go. When I say go, walk at your normal comfortable speed until I say stop"*
- Maximum speed trials: *"I will say ready, set, go. When I say go, walk as fast as you safely can until I say stop"*

8.5 Participant 1 Data Tables

10m Walk Test - Unmodified, P1				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	26.57	0.38	0.84
2	Comfortable	27.98	0.36	0.80
3	Comfortable	23.58	0.42	0.95
	Average	26.04	0.39	**0.86**
4	Fast	16.73	0.60	1.34
5	Fast	18.91	0.53	1.18
6	Fast	18.09	0.55	1.24
	Average	17.91	0.56	**1.25**

10m Walk Test - Foam, P1				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	17.9	0.56	1.25
2	Comfortable	20.08	0.50	1.11
3	Comfortable	19.98	0.50	1.12
	Average	19.32	0.52	**1.16**
4	Fast	15.53	0.64	1.44
5	Fast	14.06	0.71	1.59
6	Fast	15.69	0.64	1.43
	Average	15.09	0.66	**1.49**

10m Walk Test - Button, P1				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	17.18	0.58	1.30
2	Comfortable	16.69	0.60	1.34
3	Comfortable	16.37	0.61	1.37
	Average	16.75	0.60	**1.34**
4	Fast	14.14	0.71	1.58
5	Fast	13.84	0.72	1.62
6	Fast	15.31	0.65	1.46
	Average	14.43	0.69	**1.55**

Hip Angles, Participant 1			
	Unmodified	Foam	Button
Average (deg)	7.67	5.74	3.63
Standard Deviation	1.3	1.65	0.71

8.6 Participant 2 Data Tables

10m Walk Test - Button, P2				
Trial #	Effort	Time (s)	Speed (m/s)	Speed (mph)
1	Comfortable	61.96	0.16	0.36
2	Comfortable	58.99	0.17	0.38
3	Comfortable	58.52	0.17	0.38
	Average	59.82	0.17	**0.37**
4	Fast	53.13	0.19	0.42
5	Fast	54.17	0.18	0.41
6	Fast	46.62	0.21	0.48
	Average	51.31	0.20	**0.44**

10m Walk Test - Unmodified, P2				
Trial #	Effort	Time (s)	Speed (m/s)	Speed (mph)
1	Comfortable	62.05	0.16	0.36
2	Comfortable	69.39	0.14	0.32
3	Comfortable	64.14	0.16	0.35
	Average	65.19	0.15	**0.34**
4	Fast	67.87	0.15	0.33
5	Fast	82.37	0.12	0.27
6	Fast	76.22	0.13	0.29
	Average	75.49	0.13	**0.30**

Time Foot Contacts Ground During 1 Step (½ Gait Cycle)			
Shoe Type	Avg Length of Step (s)	Avg Time on Ground (s)	Percent of Step
Unmodified	0.77	0.28	36.6 %
Foam	0.72	0.40	55.4 %
Button	0.7	0.42	60.5 %

Hip Angles, Participant 2			
	Unmodified	Foam	Button
Average (deg)	16.44	7.11	9.63
Standard Deviation	1.52	0.63	0.47

8.7 Participant 3 Data Tables

10m Walk Test - Unmodified, P3				
Trial #	Effort	Time (s)	Speed (m/s)	Speed (mph)
1	Comfortable	8.42	1.19	2.66
2	Comfortable	8.5	1.18	2.63
3	Comfortable	7.69	1.30	2.91
	Average	8.20	1.22	**2.73**
4	Fast	5.2	1.92	4.30
5	Fast	5.49	1.82	4.07
6	Fast	5.58	1.79	4.01
	Average	5.42	1.85	**4.13**

10m Walk Test - Button, P3				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	9.46	1.06	2.36
2	Comfortable	9.33	1.07	2.40
3	Comfortable	8.71	1.15	2.57
	Average	9.17	1.09	**2.44**
4	Fast	5.82	1.72	3.84
5	Fast	5.34	1.87	4.19
6	Fast	5.41	1.85	4.13
	Average	5.52	1.81	**4.06**

10m Walk Test - Foam, P3				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	10.48	0.95	2.13
2	Comfortable	10.13	0.99	2.21
3	Comfortable	10.22	0.98	2.19
	Average	10.28	0.97	**2.18**
4	Fast	5.62	1.78	3.98
5	Fast	5.04	1.98	4.44
6	Fast	5.29	1.89	4.23
	Average	5.32	1.88	**4.22**

8.8 Participant 4 Data Tables

10m Walk Test - Button, P4				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	15.59	0.64	1.43
2	Comfortable	13.07	0.77	1.71
3	Comfortable	12.62	0.79	1.77
	Average	13.76	0.73	**1.64**
4	Fast	10.72	0.93	2.09
5	Fast	10.17	0.98	2.20
6	Fast	10.4	0.96	2.15
	Average	10.43	0.96	**2.15**

10m Walk Test - Foam, P4				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	14.49	0.69	1.54
2	Comfortable	13.8	0.72	1.62
3	Comfortable	13.99	0.71	1.60
	Average	14.09	0.71	**1.59**
4	Fast	12.04	0.83	1.86
5	Fast	12.21	0.82	1.83
6	Fast	12.83	0.78	1.74
	Average	12.36	0.81	**1.81**

10m Walk Test - Unmodified, P4				
Trial #	**Effort**	**Time (s)**	**Speed (m/s)**	**Speed (mph)**
1	Comfortable	18.43	0.54	1.21
2	Comfortable	15.09	0.66	1.48
3	Comfortable	15.84	0.63	1.41
	Average	16.45	0.61	**1.37**
4	Fast	12.83	0.78	1.74
5	Fast	12.83	0.78	1.74
6	Fast	12.75	0.78	1.75
	Average	12.80	0.78	**1.75**

Time Foot Contacts Ground During 1 Step (½ Gait Cycle)			
Shoe Type	**Avg Length of Step (s)**	**Avg Time on Ground (s)**	**Percent of Step**
Unmodified	0.79	0.31	39.7 %
Foam	0.76	0.28	37.2 %
Button	0.70	0.39	55.8 %

Hip Angles, Participant 3			
	Unmodified	Foam	Button
Average (deg)	5.45	4.27	1.87
Standard Deviation	0.85	2.31	1.52